Advances in Applied Sciences
2021; 6(4): 88-105
http://www.sciencepublishinggroup.com/j/aas
doi: 10.11648/j.aas.20210604.14
ISSN: 2575-2065 (Print); ISSN: 2575-1514 (Online)

New Lights on Mineralogical and Geochemical Characteristics of Cretaceous Rocks, Gabal Qabaliat Area, South West Sinai, Egypt

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To cite this article:

Mahmoud Ahmed El Ammawy, Bothaina Mohamed Moussa, Refaat Abdelkareem Osman, Gamal Mohamed El Qot, El Sayed Ali El Abd. New Lights on Mineralogical and Geochemical Characteristics of Cretaceous Rocks, Gabal Qabaliat Area, South West Sinai, Egypt. *Advances in Applied Sciences*. Vol. 6, No. 4, 2021, pp. 88-105. doi: 10.11648/j.aas.20210604.14

Received: August 23, 2021; **Accepted**: September 3, 2021; **Published**: November 5, 2021

Abstract: The Cretaceous sedimentary succession at Gabal El-Qabaliat range in age from Aptian-Albian to Maastrichtian. Lithostratigraphically, the succession is subdivided into Malha, Raha, Abu Qada, Wata, Matulla and Sudr formations. The mineralogy of bulk samples of Malha Formation reveals one association (quartz, kaolinite, anhydrite, muscovite and calcite followed by dolomite). The Raha Formation reveals the presence of two cycles of environmental conditions. (calcite then quartz, kaolinite and gypsum; quartz, halite, hematite, muscovite, kaolinite and gypsum). Abu Qada Formation has two cycles of environmental conditions (quartz, halite, montmorillonite, kaolinite, muscovite and calcite; quartz, anhydrite, glauconite and hematite) but Wata Formation has one cycle (calcite, dolomite and quartz). Matulla Formation has four associations (calcite, dolomite, anhydrite, hematite, quartz; calcite, dolomite, quartz, goethite, hematite and gypsum; quartz, goethite, gypsum, calcite, hematite, glauconite, kaolinite; quartz, montmorillonite, halite, anhydrite, muscovite and calcite). The clay mineralogy of Raha Formation reveals one clay association (montmorillonite, saponite and kaolinite), but Abu Qada Formation reveals the presence of two cycles of environmental conditions (lower one: kaolinite, chlorite, saponite, illite and goethite; second: montmorillonite, saponite, chlorite=kaolinite, goethite). Matulla Formation has two clay associations [montmorillonite with monor illite, saponite > kaolinite (lower cycle; middle part of this formation), montmorillonite= saponite (2nd cycle)]. Form the geochemical studies, the variation in each major oxides and trace elements either in clastic or non-clastic rocks discussed revealing the kind of clay mineral associations and other minor components present. Two groups were identified based on CaO and MgO contents; 1st group has > 54% CaO and low MgO including Raha, Matulla and Sudr limestones while the other group including the moredolomitic facies of Abu Qada. The dolomitic facies of Abu Qada exhibit high CaO compared with the Wata and Matulla formations. Four groups were identified based on SiO_2 and CaO contents, the 1st group has <1% SiO_2 and > 54% CaO including Sudr, Matulla and Raha limestones; the 2nd one has 1-2.2% SiO_2 and 47-54% CaO including Abu Qada samples; the 3rd one has ~3% SiO_2 and 35% CaO as in Wata dolomitic limestone and the 4th one has 27% SiO_2 and 37% CaO including dolomitic limestone of Matulla Formation. Ba and Sr contents of limestone facies reflect a separation between the different types, where Ba contents of dolomitic facies are more than their contents in limestone facies of Abu Qada, Wata, and Matulla. The Sr contents have the opposite trend where Sr content of limestone are more than that of dolomitic facies (Raha and Matulla).

Keywords: Mineralogical, Geochemical, Cretaceous, Gabal Qabaliat

1. Introduction

The considered Gabal El-Qabaliat area occupies ab. 36 Km^2 SW Sinai, Egypt (Long. 33° 26' & 33° 35' E; Lat. 28° 31' & 28° 18' N), Figure 1. Several studies have contributed to the general geology of the area as in Issawi et al. [12], Bunter [6], Abdel-Hamid et al. [1], Shahin [19], Allam & Khalil [4], Cherif et al. [7, 8], El-Aassy et al. [9], Mansour et al. [16], Abdel_Gawad et al. [2] and Anan &Wanas [5].

The present investigation is mainly concerned with clay mineralogy (X-ray diffraction of bulk and clay samples) and geochemical characteristics of Cretaceous rocks from two surface sections (A&B). The XRD technique has been carried out on 37 sedimentary samples representing the sedimentary succession in these two sections (21 non-oriented samples of carbonate, sandstone and shale; 8 oriened samples of clays and shales). Eleven sedimentary samples are chosen for the geochemical characteristics at Geological Survey of Egypt (11 samples for major and 11 samples for trace elements).

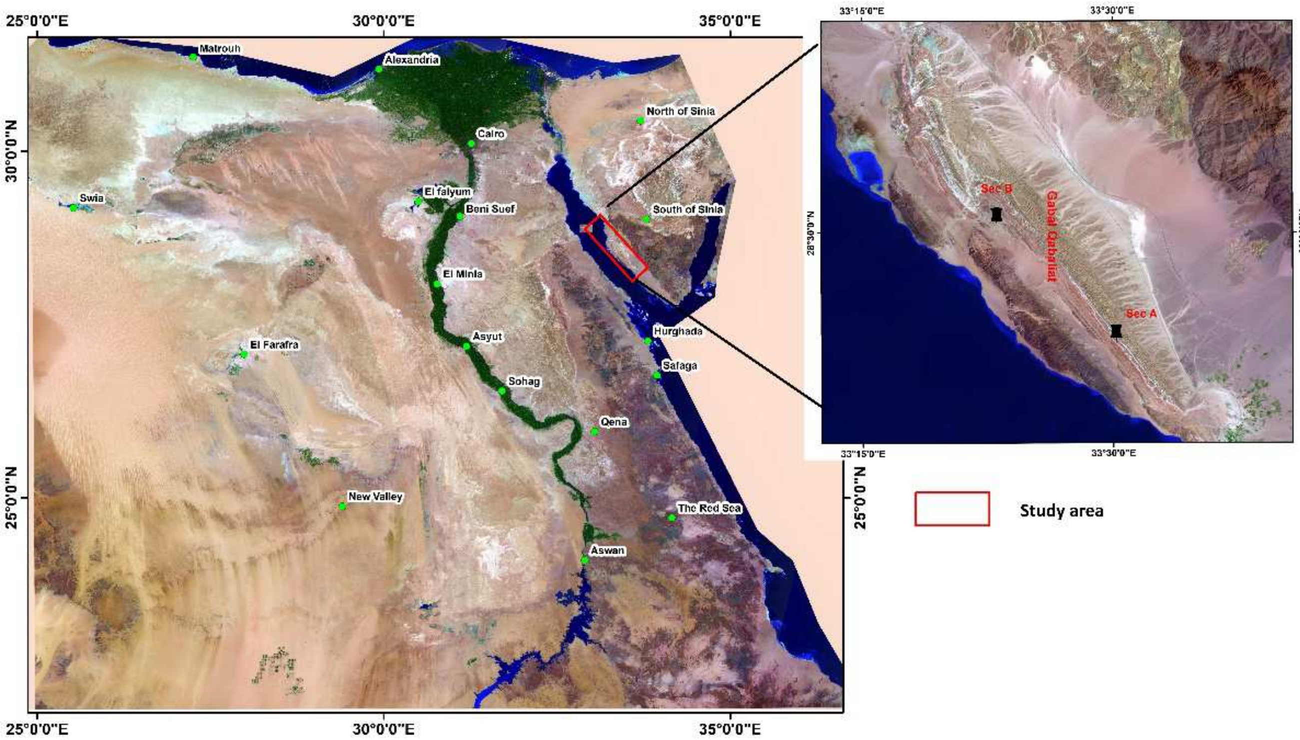

Figure 1. *Location map of the studied area.*

2. Geologic Setting

The Cretaceous sedimentary succession in Gabal El-Qabaliat range in age from Aptian-Albian to Maastrichtian.

Lithostratigraphically, the succession is subdivided into the Malha, Raha, Abu Qada, Wata, Matulla and Sudr formations. Two measured surface sections were sampled from the Gabal El-Qabaliat (Aptian-Albian to Maastrichtian).

Out of 125 samples from the two sections (A&B) were studied based on lithologic characters established from the field observations and laboratory descriptions, in additionto the types of sedimentary structures. The composite stratigraphic succession shows that the Malha Formation is composed mainly of argillaceous, ferruginous sandstone. The Raha Formation consists of shale, dolomitic limestone and limestone. The Abu Qada Formation consists of shale and sandstone with minor limestone, but the Wata Formation is composed of limestone with few shale beds. The Matulla Formation consisits of shale, sandstone and limestone, the Sudr Formation is composed mainly of chlak and chalky limestone.

3. Methodology

XRD technique was used to identify the clay mineralogy as well as associated minerals in the different lithologic facies. The wet chemical analytical techniques were used to determine the major oxide compositions of the sediments. Some selected trace elements related to sediment provenance and environmental indicators were determined by XRF technique. The chemical data are correlated to mineralogical ones and interpreted in terms of provenance and geochemical history of the studied sediments.

By the results obtained, the relationships between the properties of sedimentary deposits and their geochemical characteristics are revealed.

4. Discussion and Results

4.1. Mineral Composition

The XRD technique has been carried out on 37 samples representing the sedimentary succession encountered in the two stratigraphic surface sections (A&B). Twenty-nine non-oriented samples of carbonate, sandstone, shale and eight parallel oriented samples of clays and shale have been undertaken after the essential pre-treatments.

They represent the rock units of Early Cretaceous (Malha Formation) and Late Cretaceous times (Cenomanian and Turonian; Raha, Abu Qada and Wata formations; Coniacian-Santonian, Matulla then Maastrichtian, Sudr formations). The mineral composition and their interpretation are encountered from base to top as follows:

4.1.1. Malha Formation (Aptian-Albian)

The X-ray diffractograms of the bulk sandstone samples at the middle part of this Formation reveal the predominance of quartz, kaolinite, anhydrite, muscovite and calcite followed by dolomite (Figure 2).

The lithology of this Formation (sandstones) indicates the fluvio-parallic to shallow marine conditions.

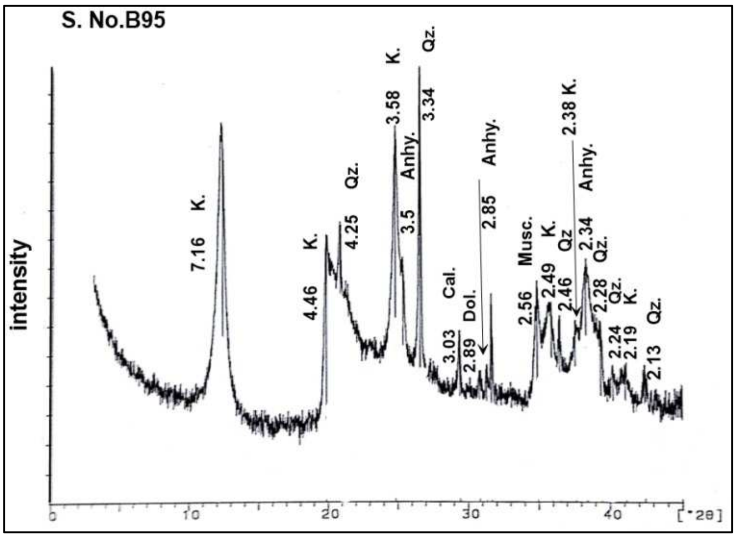

Figure 2. *X-ray diffractogram of bulk sample, Malha Formation, Qabaliat area.*

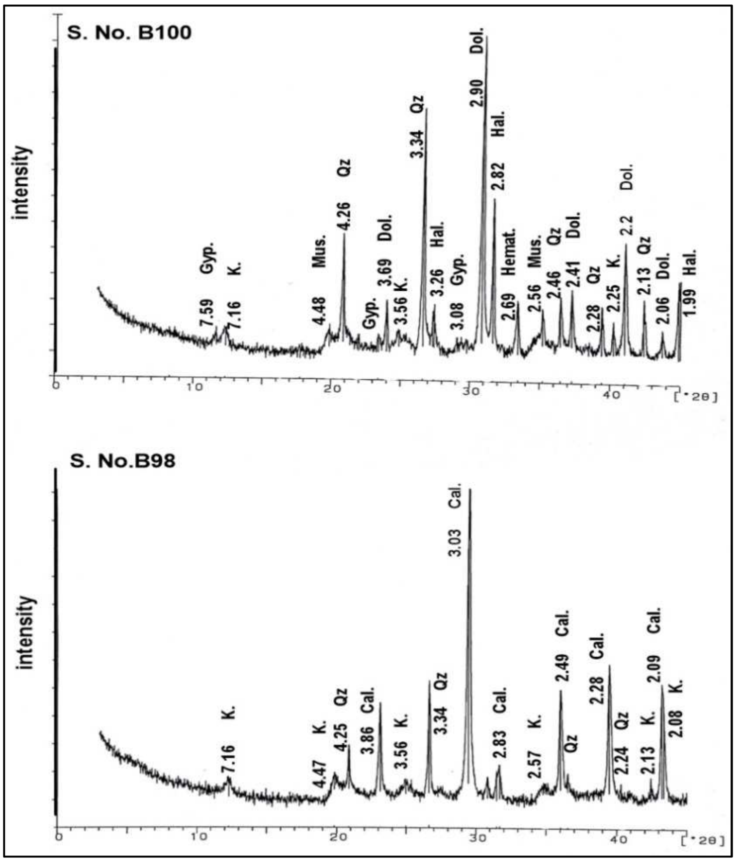

Figure 3. *X-ray diffractograms of bulk samples from Raha Formation, Qabaliat area.*

4.1.2. Raha Formation (Cenomanian)

The X-ray diffractograms of the bulk samples of non-clastic deposits reveal the predominant of calcite then quartz and kaolinite or gypsum but at S.No.B100 reveals that dolomite is more predominance the quartz, halite, hematite, muscovite, kaolinite and gypsum (Figure 3). But the bulk carbonate samples clarify that mineral dominated then dolomite and quartz. It is concluded that the calcite and dolomite followed by quartz and kaolinite are dominated reflecting marine conditions.

The mineralogic composition of this formation (clay minerals) reveals that the clay fraction are characterized by the dominance of montmorillonite then saponite and kaolinite (Figure 4). The clay mineral association indicates slightly alkaline to slightly acidic pH environment.

It is clarified that during the deposition of Raha Formation the marine sea invaded the continent where Mg^{2+} are rich from Mg clays (alkaline pH environment).

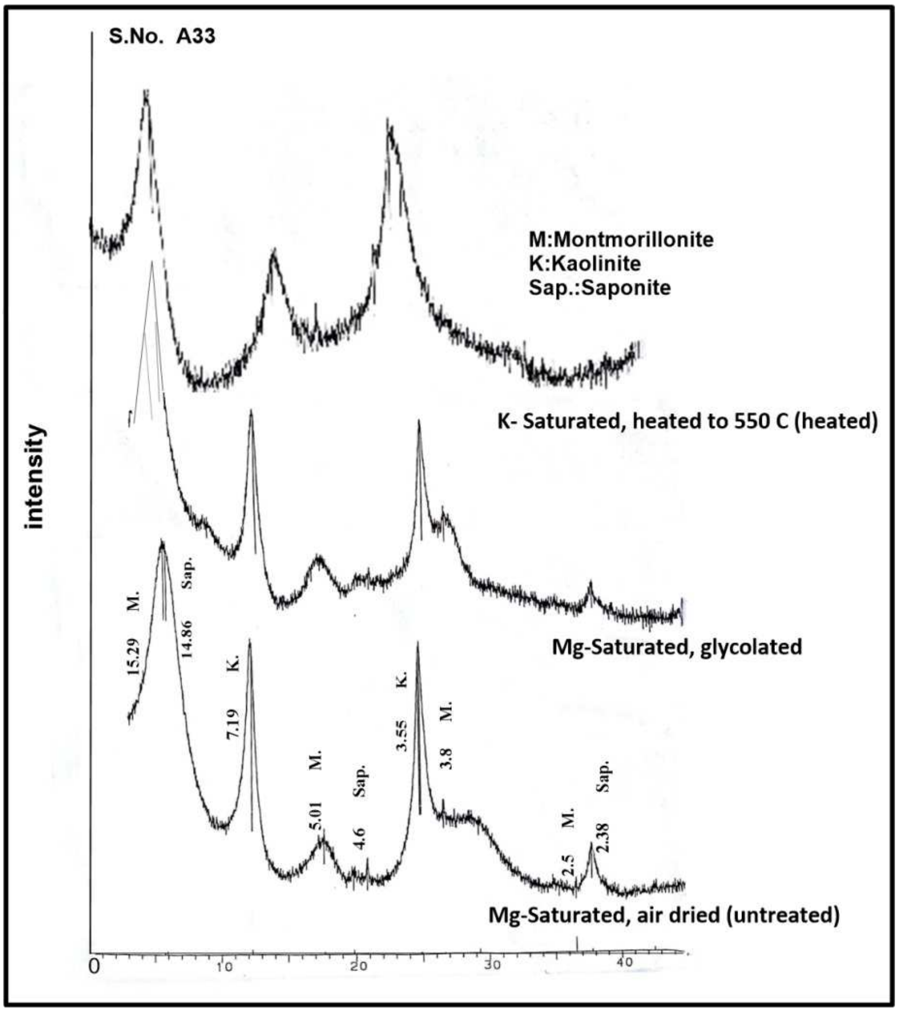

Figure 4. X-ray diffractograms of selected clay sample, Raha Formation, Qabaliat area.

4.1.3. Abu Qada Formation (Early Turonian)

The X-ray diffractograms of the clastic samples reveal the predominance of quartz the halite, montmorillonite, kaolinite, muscovite and calcite changing upward to quartz then anhydrite, glauconite and hematite at section (A). At section (B), the data reveal the predominance of quartz then halite, kaolinite, muscovite and montmorillonite (S.No.B106) but in sample No. B107 the quartz then halite, anhydrite, goethite, kaolonite, montmorillonite and muscovite. With respect to bulk samples of carbonates, the XRD reveal that dolomite is dominated followed by quartz the goethite (S.No.A48) but calcite mineral dominated followed by quartz, illite then kaolinite in S.No.A52. The data of S.No.B105 reveal that dolomite is a predominant mineral then hematite (Figure 5).

The fore-mentioned associations reveal the prevealing of marine condition followed upward by a regressive phase (presence of halite and anhydrite). The shallowing up conditions following the Cenomanian ramp was mentioned by Issawi et al. [13].

The obtained X-ray diffractograms of clay samples reveal the abundance of kaolinite, saponite then montmorillonite (S.No.A52). At section (B), the mineral composition of this formation at its lower part reveal that kaolinite, chlorite, saponite, illite the goethite (S.No.B106) changed upward to montmorillonite, saponite, chlorite=kaolinite then goethite (S.No.B107), (Figure 6).

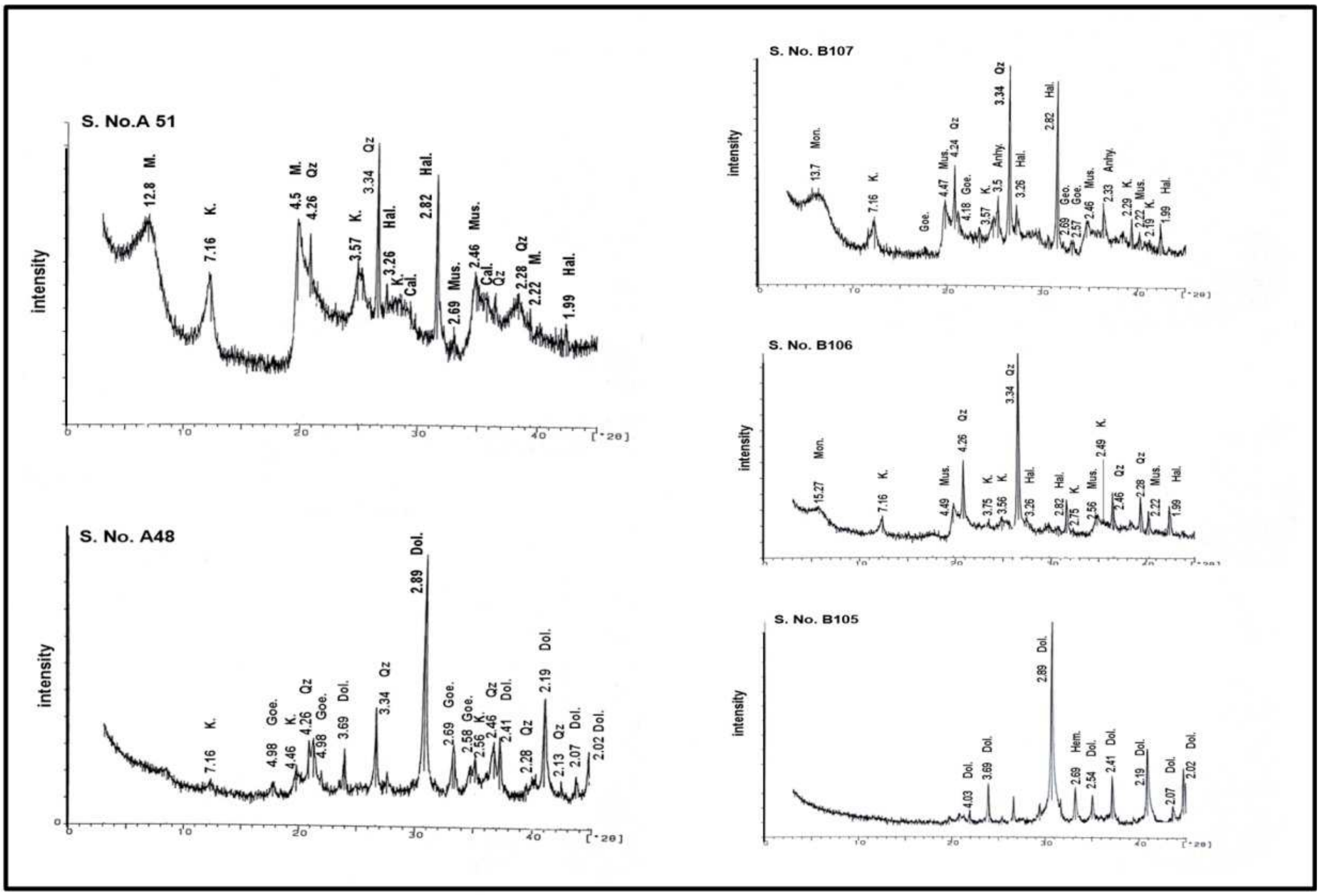

Figure 5. *X_ray diffractogram of bulk sample from Abu Qada Formation, Section (A& B) Qabaliat area.*

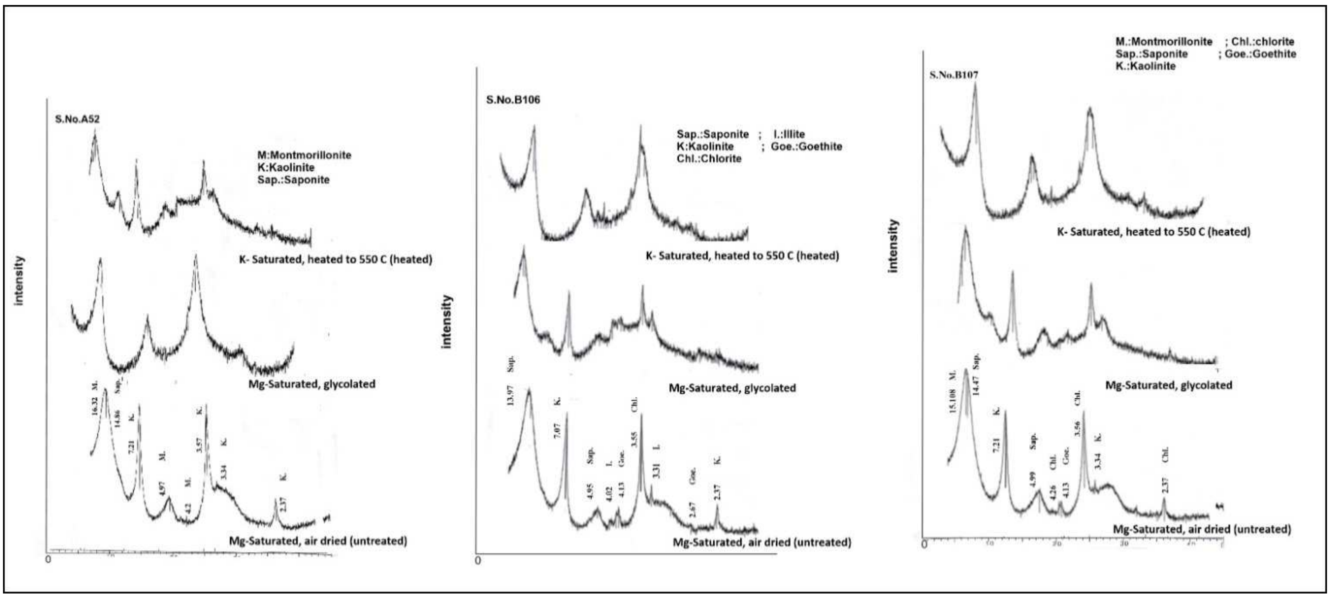

Figure 6. *X-ray diffractograms of selected clay sample, Abu Qada Fm., sections (A &B).*

This formation shows according to the distribution of the clay mineral association two cycles of environmental conditions. The lower cycle exhibits the clay mineral association kaolinite > chlorite > saponite > illite > goethite indicating slightly acidic to slightly alkaline pH environment. The presence of small amounts of illite may indicate that kaolinite was formed due to hydrolysis of muscovite &/or feldspars in the source rocks. The second cycle exhibits clay mineral association montmorillonite > saponite> chlorite+kaolinite>goethite indicating slightly alkaline to slightly acidic pH environments.

The saponite is considered as resulting from the reaction between detrital mineral and Si- &Mg- rich solutions Jones &Galan, [14]. The illite content decreases up section due to farness from any direct continental influence. Kaolinite is generally of exogenic surficial origin, forming during the weathering of alumino-silicates in igneous, metamorphic and occasionally sedimentary rocks but it is occasionally authigenic formed in an acid environment. It is also precipitated from solutions circulating through sedimentary rocks; this process is commonly accompanied by the replacement of other minerals. Also, kaolinite is formed much more slowly in well-drained areas where fluids have a low ionic strength. The favourable conditions for its formation implies high Al:Si ratio, an acid environment and absence of Na^+, K^+, Ca^{2+}, $Mg^{2+}$and Fe^{2+} Keller, [15].

4.1.4. Wata Formation (Late Turonian)

The X-ray diffractograms of the bulk samples of the carbonate at section (A) reveal that the presence of calcite as a predominant mineral followed by quartz and hematite at the lower part (S.No.A55), then by calcite, dolomite and quartz at the upper part (S.No.A57). (Figure 7).

The Wata Formation was deposited in low energy subtidal environment Ahmed & Osman, [3]. It represents a transgressive phase at the end of the Turonian (presence of calcite and dolomite) following the distinct regressive phase (presence of few intercalation of calcareous claystone along with anhydrite, halite anf quartz) during the lime of Abu Qada Formation (phase of beginning of the Turonian).

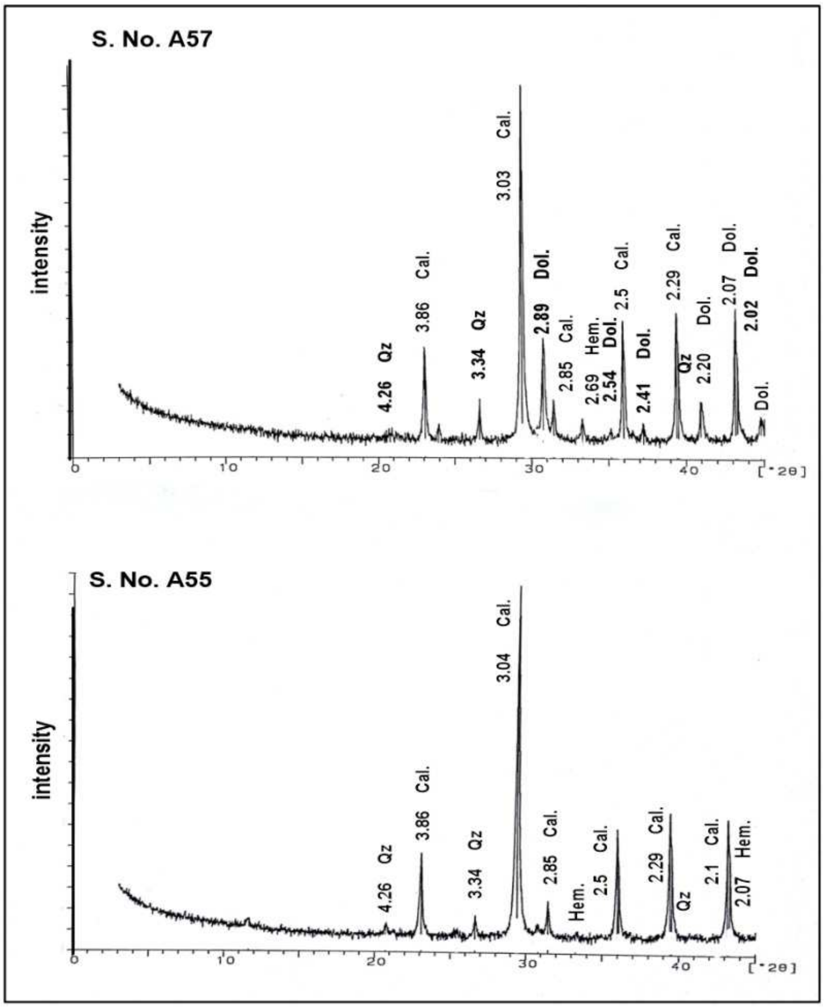

Figure 7. *X-ray diffractograms of selected clay sample, Wata Fm., section (A).*

4.1.5. Matulla Formation (Coniacian-Santonian)

The X-ray diffractograms of carbonates reveal that calcite mineral predominate then dolomite, quartz, goethite, hematite (S.No.A71); but calcite then quartz and halite at S.No.A89 but calcite, dolomite then anhydrite, hematite, quartz, goethite (S.No.B110'); calcite then dolomite, quartz, apatite, hematite, goethite (S.No.B117); calcite then dolomite, quartz, goethite, hematite, muscovite, gypsum at S.No.B119. The mineral composition of clastic deposits reveal that quartz mineral predominate then calcite, montmorillonite, halite, muscovite and hematite (S.No.A64). Going upward, it is changed into quartz, montmorillonite, kaolinite, anhydrite, halite then glauconite (S.No.A69). More upward it declares the predominance of quartz, montmorillonite, muscovite, halite and anhydrite (S.No.A78). The mineral composition of clastic deposits reveal that quartz predominate then goethite, gypsum, calcite, hematite, glauconite and kaolinite (S.No.B110); quartz, glauconite, kaolinite, siderite and hematite (S.No.B111) with respect to sandstone samples but quartz, halite, anhydrite, montmorillonite, kaolinite, muscovite, calcite (S.No.B115) and quartz, montmorillonite, halite, anhydrite, muscovite, calcite (S.No.B121) with respect to argillaceous samples. Although near the top of this formation, there is a gypsum band characterized by halite, quartz, siderite, dolomite, anhydrite, goethite, muscovite and calcite (S.No.B120), Figure 8.

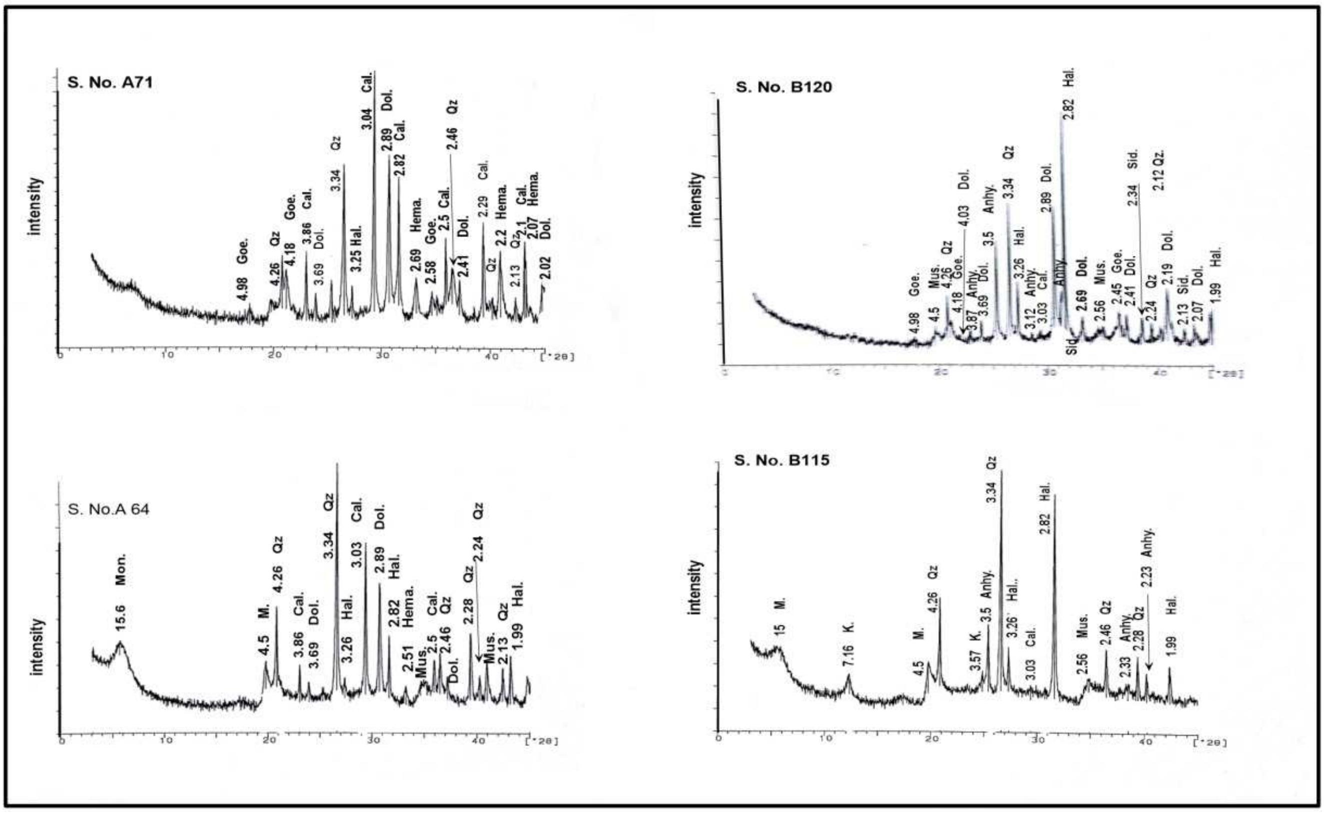

Figure 8. *X-ray diffractograms of bulk samples, Matulla Formation, sections (A &B).*

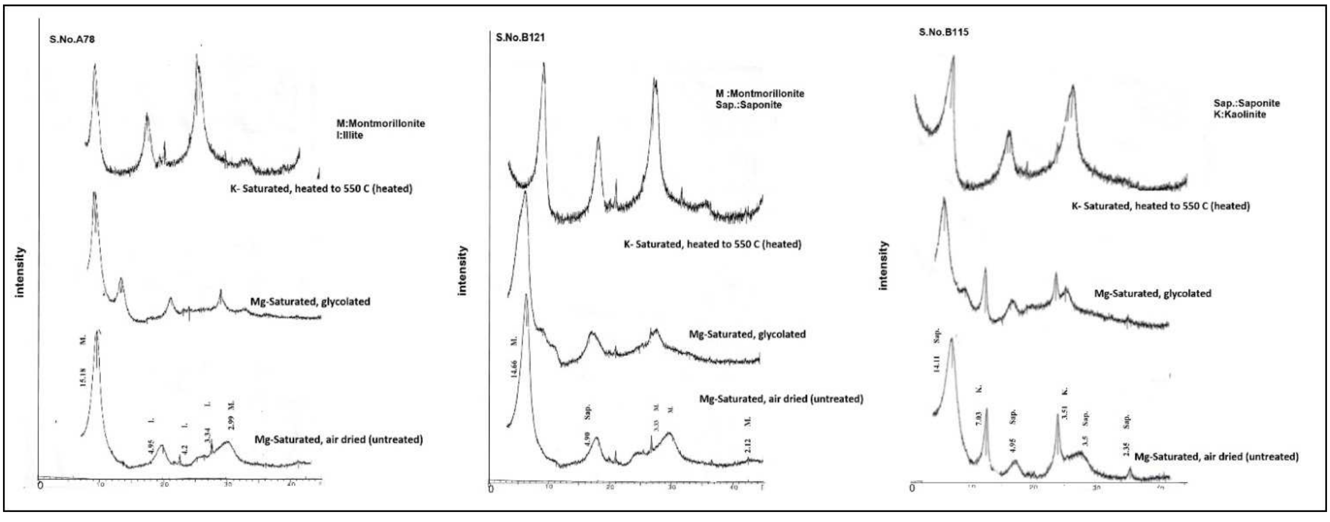

Figure 9. *X-ray diffractogram of selected clay sample, Matulla Formation.*

From the above discussion, it can be stated that the base of this Formation indicating deeper depth contains calcite, dolomite but at the upper part it contains halite, quartz, anhydrite reflecting shallowness of sea water.

Regarding the mineral composition of the Matulla Formation from the middle part of this Formation reveal that montmorillonite is predominant with minor amounts of illite (S.No.A78) changed upward to saponite then kaolinite (S.No.B115). The top middle part of this formation is dominated by montmorillonite and saponite (S.No.B121), (Figure 9).

This formation shows according to the distribution of the clay mineral association two cycles of environmental condition. The lower cycle (middle part of this formation) exhibits the clay mineral association montmorillonite with minor amounts of illite and also saponite > kaolinite indicating slightly alkaline to slightly acidic pH environment. The presence of small amounts of illite may indicate that kaolinite was formed due to hydrolysis of muscovite and/or feldspars in the source rocks. The second cycle exhibits clay mineral associations montmorillonite=saponite indicating more alkaline pH environment.

4.1.6. Sudr Formation (Maastrichtian)

This formation is recorded in section (B). It consists mainly of carbonate deposits. The X-ray diffractogram of bulk samples of the carbonate sample reveals the presence of calcite only (S.No.B125), (Figure 10). It represents a transgressive phase during Maastrichtian time.

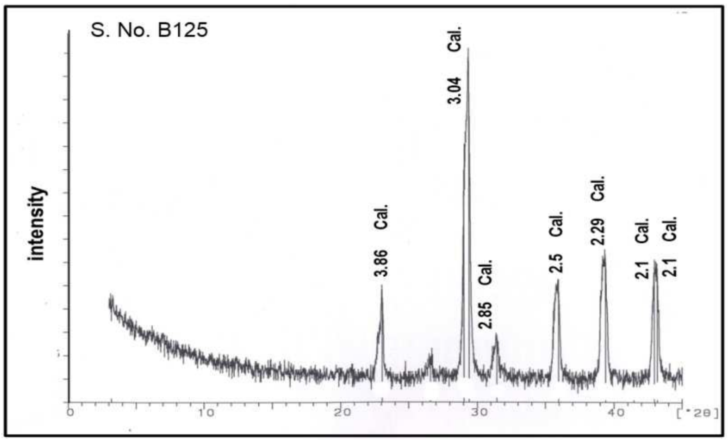

Figure 10. *X-ray diffractogram of bulk sample, Sudr Formation.*

4.2. Geochemical Characteristics

The major chemical analyses are made for lower Cretaceous (Malha Fm.) to Campanian-Maastrichtian (Matulla Fm.) rocks.

Eleven samples (Malha, Raha, Abu Qada, Wata and Matulla) were carried out either to major oxides or trace elements (Cr, Ni, Cu, Zn, Zr, Rb, Y, Ba, Pb, Sr, Ga, V & Nb).

4.2.1. Clastic Rocks

The major constituents were determinted in the analyzed samples representing section (A) [Raha sandstone (S.No.A19); Abu Qada shale (S.No.A51) and Matulla sandstone (S.No.A59, A66, A80, A89)] and section (B) [Malha sandstone (S.No.B95); Raha shale (S.No.B96); Abu Qada shale (S.NO.B106) and Matulla sandstone (S.No.B110), shale (S.No.B115). The behavior and distribution of the major oxides are shown on Figure 11. The data of the analyzed samples represent the different formations as shown in Table 1.

The studied sandstone samples exhibit a general increase in the silica content with the decrease in the age from Cenomanian to Coniacian-Santonian, whereas the data of shale samples reveal that the silica content is nearly constant in the decrease in age.

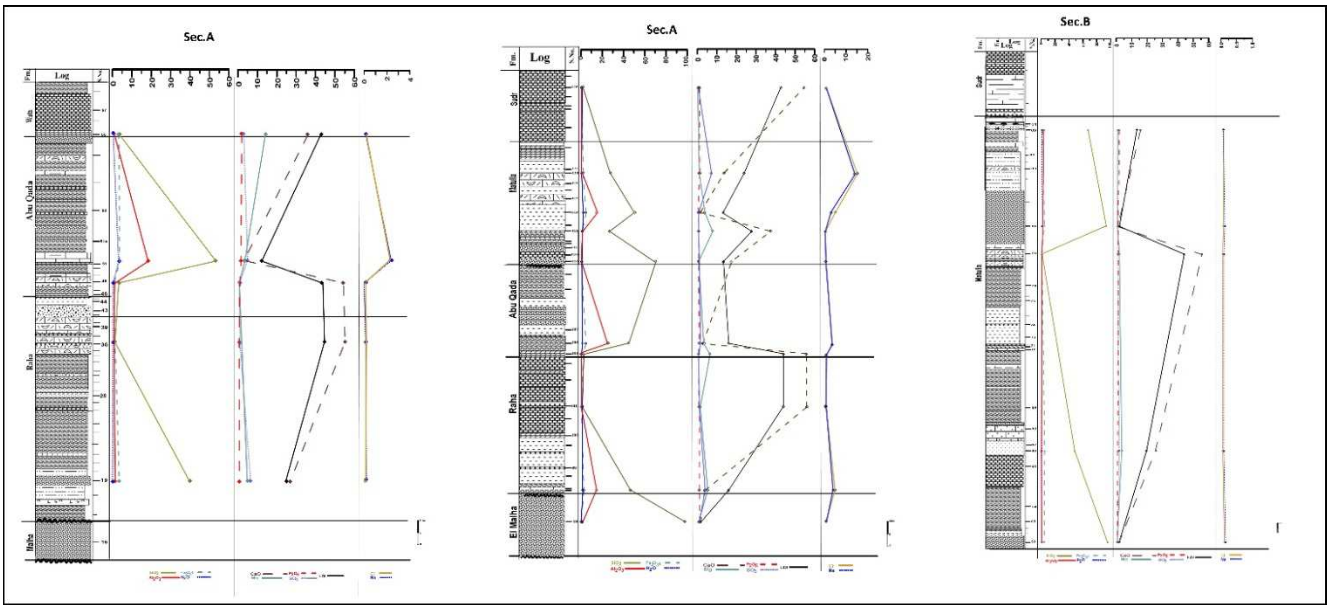

Figure 11. *Major oxides versus lithology of Qabaliat, sections (A & B).*

Table 1. *Major oxides (XRF%) and some ratios of some representative clastic samples, sections A&B, Gabal Qabaliat.*

Sp. No.	**Clastic rocks**										
	Malha Fm.	**Raha Fm.**		**Abu Qada Fm.**		**Matulla Fm.**					
Oxides%	**B95**	**A19**	**B96**	**A51**	**B106**	**A59**	**A66**	**A80**	**A89**	**B110**	**B115**
SiO_2	97.5	38.88	47.34	51.32	44.15	94.05	47.2	94.62	67.4	70.6	51.65
TiO_2	0.08	0.02	1.21	1.25	1.14	0.29	0.07	0.37	0.23	0.01	2
Al_2O_3	1.43	0.29	17.15	18	24.24	0.97	0.53	0.99	2.04	0.03	16.89
Fe_2O_{3t}	0.17	1.71	2.84	2.75	4.55	2.2	2.89	2.29	0.84	0.06	4.49
CaO	0.03	26.25	1.97	2.35	1.97	0.29	24.99	0.06	15.27	16.21	1.51
MgO	0.02	3.48	4.44	3.38	2.42	0.04	2.63	0.02	0.15	0.03	3.11
MnO	0.01	0.2	0.03	0.03	0.04	0.02	0.23	0.01	0.05	0.01	0.04
Na_2O	0.03	0.01	1.44	2.09	2.02	0.05	0.01	0.04	0.01	0.01	1.69
K_2O	0.02	0.01	1.54	1.86	1.04	0.34	0.26	0.85	0.17	0.01	0.88
P_2O_5	0.01	0.01	0.08	0.12	0.21	0.07	0.25	0.01	0.67	0.01	0.07
Cl^-	0.01	0.01	3.68	2.14	2.31	0.03	0.01	0.01	0.01	0.01	4.5
SO_3^{--}	0.01	4.9	2.46	2.6	0.23	0.34	0.94	0.01	0.01	0.01	0.01
LOI	0.5	23.93	15.52	11.92	15.49	1.11	19.64	0.54	12.78	12.74	12.73
Total	99.82	99.7	99.70	99.81	99.81	99.80	99.65	99.82	99.63	99.74	99.57
K_2O/Na_2O	0.6666	1	1.069	0.8899	0.5148	6.8	26	21.25	17	1	0.520
SiO_2/Al_2O_3	68.18	134.07	2.76	2.85	1.82	96.96	89.06	95.58	33.04	2353.30	3.06
log SiO_2/Al_2O_3	1.83	2.13	0.44	0.46	0.26	1.99	1.95	1.98	1.52	3.37	0.49
log Na_2O/K_2O	0.18	0.00	-0.03	0.05	0.29	-0.83	-1.41	-1.33	-1.23	0.00	0.28
log Fe_2O_3/K_2O	0.93	2.23	0.27	0.17	0.64	0.81	1.05	0.43	0.69	0.78	0.71
Fe_2O_3+MgO	8.50	0.49	0.64	0.81	1.88	55.00	1.10	114.50	5.60	2.00	1.44

The studied sandstone samples exhibit alumina content of ~1%, ~0.3% and 0.03-2% at Malha, Raha and Matulla formations, respectively. The shale samples have content of ~18%, ~18-~24% and ~17% at Raha, Abu Qada and Matulla formations, respectively.

The shale samples in the two sections show +ve coherence between silica and alumina indicating that both oxides are carried mainly in the clay minerals (Figure 11).

The studied sandstone samples exhibit Fe_2O_3 content of ~0.2%, ~2%, ~0.1-~0.8% at Malha, Raha and Matulla formations, respectively. The shale samples have content of ~3% and ~5% at Abu Qada and Matulla formations, respectively. There are an increase of Fe_2O_3 content in shale samples than at sandstone samples and also with increasing age as in Abu Qada and Matulla.

The distribution of manganese (Mn) in the studied sandstone samples is 0.01%, ~0.2% and 0.01-0.2% at Malha, Raha and Matulla formations, respectively. Its distribution is partly controlled by the provenance and partly by coherence with other elements as iron.

The studied sandstone samples exhibit MgO content of 0.02%, ~3%, 0.02- ~3% at Malha, Raha, Matulla formations, respectively. The shale samples have content of ~4%, ~2-~3%, ~3% at Raha, Abu Qada and Matulla formations, respectively. The High MgO content reflects the presence of algae in the studied shales.

The studied sandstone samples exhibit CaO content of 0.03%,~26%, 0.06-25% at 1%; ~2%, ~1.5% at Raha, Abu Qada and Matulla formations, respectively. The high CaO content reflect the presence of calcite mineral as fragments and/or as cement.

The Na_2O content predominates K_2O content in the sandstone samples, but K_2O content predominates Na_2O content at Raha, Abu Qada and Matulla in the shale samples. Potassium is preferentially adsorbed by clays (Millot, 1970) while recorded sodium may be present in the form of water soluble salts (mainly halite) and/or as a constituent in the clay mineral.

The P_2O_5 content have higher content in the shale samples than at sandstone samples at Raha, Abu Qada and Matulla formations. The high content of phosphorus is related to bone fragments as in S.No.A89.

The studied sandstone samples exhibit $SO_3^-$and Cl^- content of 0.01% to either of them, ~5% and 0.01%; 0.01%-1% and 0.01%-0.03% at Malha, Raha and Matulla formations, respectively. The shale samples have content of ~3% and ~2%; 0.01% and ~5% at Abu Qada and Matulla formations, respectively. The high content of $SO_3^{--}$and Cl^- in the shale samples are due to the presence of gypsum streaks.

From the previous discussion, it is concluded that generally the studied sandstone samples have high SiO_2 and low Al_2O_3, Fe_2O_3, CaO, MgO, K_2O and LOI compared with the studied shale samples (Figure 12).

Trace elements: The trace constituents were determined in the analyzed samples representing sections (A&B). The behavior and distribution of the trace elements will be outlined and discussed as follows (Table 2, Figure 13):

Figure 13 shows the comparison between the studied clastic samples. The figure shows the following:

1. The studied Matulla shale sample (S.No.B115) exhibits

high contents of Ni, Cu, Zn, V and Ba compared with Raha and Abu Qada shale samples (S.No.B96, A51) probably related to the type of clay minerals in Matulla (chlorite) compared with montmorillonite mineral of Abu Qada shale (Table 1, Figure 13).

2. It is realized that the high Sr content at section (B, S.No.B115) 615 ppm of Matulla Formation and Raha Formation 312 ppm (S.No.B96) may be related to the calcareous nature of these samples (Table 1, Figure 13).
3. It is realized that the high Ba content of Matulla formation (1289 ppm, S.No.B115) at section (B) and at section (A) the Ba content (1721 ppm, S.No.A51, Abu Qada Fprmation) may be related to the presence of gypsum nodules.
4. Generally, the studied Raha and Matulla sandstone samples exhibit high content of trace elements compared with the sandstones of Malha and Abu Qada formations probably due to the presence of minor iron, gypsum and halite in its lithic contents.
5. Generally, the studied sandstone samples of Matulla Formation section (A; S.No.A59 & A80) exhibit enrichment of Cr, Sr and Vcompared with the other formations. At Raha, the sample No.A19 exhibits enrichment of Ni and Zn than at Matulla Formation. At section (B), the samples of Raha and Matulla exhibit enrichment of V, Zn, Sr (S.No.B110) compared with other formations. The above behavior reflects their argillaceous and clayey nature.

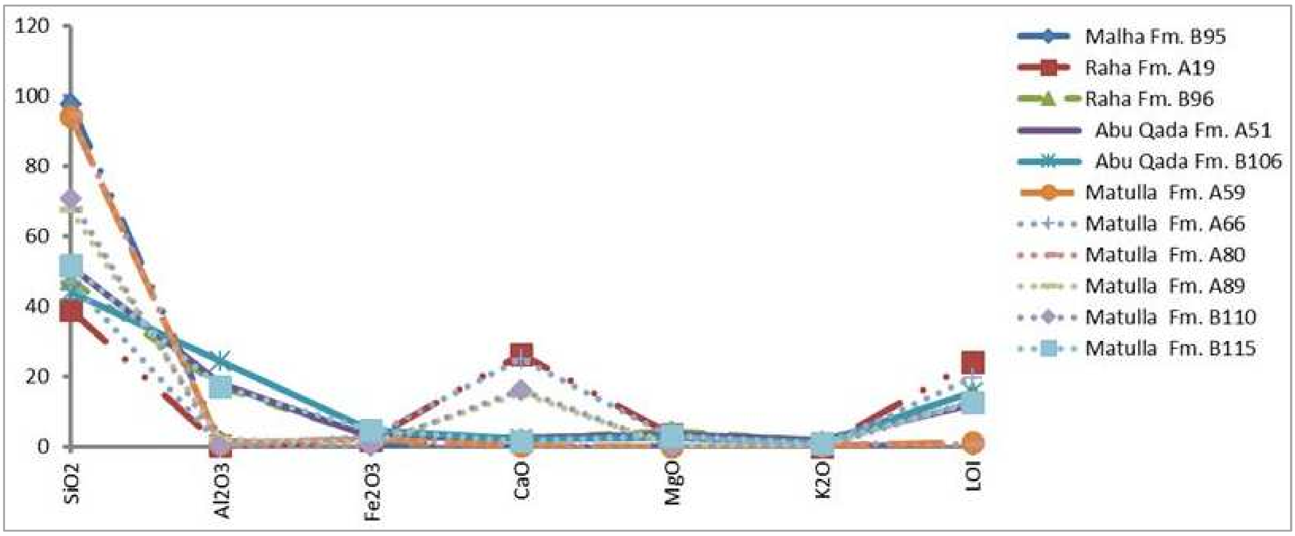

Figure 12. *Major oxide variation diagram of the studied clastic rocks in sections A&B, Gabal Qabaliat.*

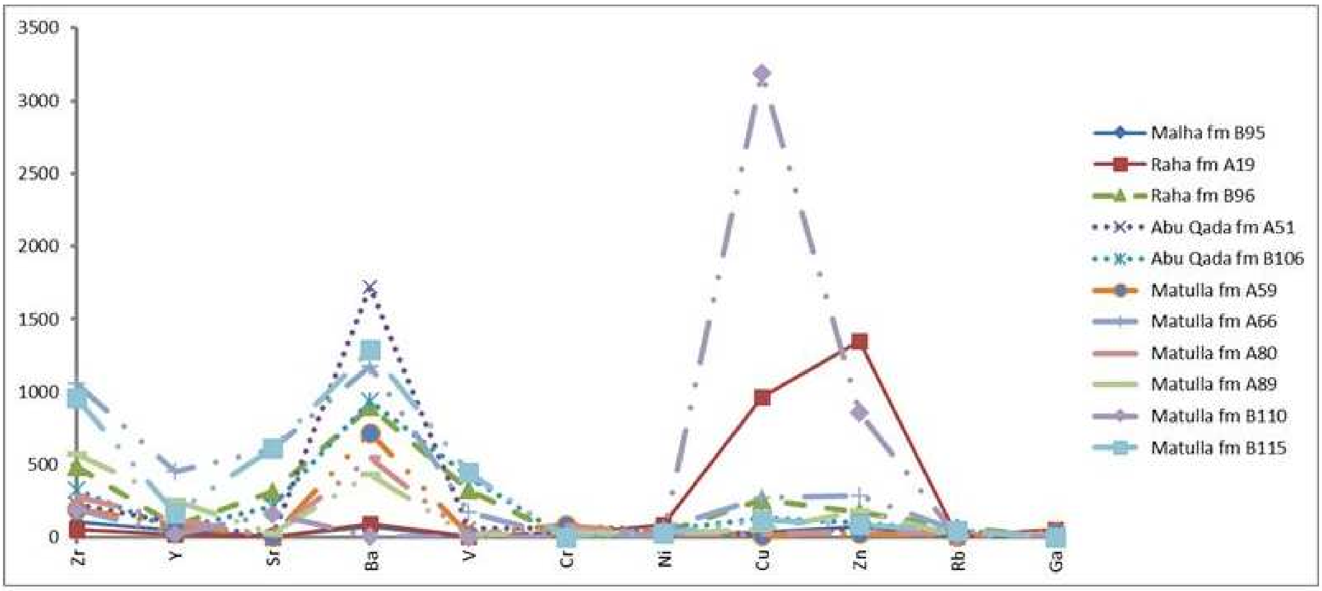

Figure 13. *Trace elements variation diagram of the studied clastic rocks, G. Qabaliat area.*

Table 2. *Trace elements (ppm) of some representative clastic samples from section A& B, Gabal Qabaliat.*

Sp. No.	**Clastic rocks**										
	Malha fm	**Raha fm**		**Abu Qada fm**		**Matulla fm**					
Elements	**B95**	**A19**	**B96**	**A51**	**B106**	**A59**	**A66**	**A80**	**A89**	**B110**	**B115**
Cr	41	19	n.m	69	n.m	86	n.m	84	34	n.m	n.m
Ni	20	86	35	59	50	40	64	28	31	20	27
Cu	38	966	260	16	135	17	274	19	58	3189	122
Zn	73	1348	176	59	98	25	288	40	181	858	89
Zr	110	57	485	226	326	191	1060	281	575	196	960
Rb	4	9	70	40	48	9	47	27	17	5	50
Y	51	24	83	99	52	85	453	123	253	19	166
Ba	73	92	898	1721	941	717	1174	548	430	8	1289
Pb	12	84	12	16	18	74	18	35	18	39	9
Sr	5	3	312	10	213	9	607	13	26	164	615
Ga	7	55	5	10	4	44	u.d	18	12	5	3
V	4	5	329	63	422	23	176	15	12	3	447
Nb	18	10	58	38	38	32	14	47	96	21	115

4.2.2. Geochemical Characteristics and Classification

Major oxides: The relationships were used either to classify the clastic rocks (a), terrigenous sediments (b) or discriminate the tectonic setting of sandstone-mudstone suites (c).

The figure of log(SiO_2/Al_2O_3) versus log(Na_2/K_2O) according to Pettijohn [17], (Figure 14) indicate that the sample of the Matulla (section A) and one sample of Raha Formation (section A) are in the Q-arenite field; the other samples of Matulla (S.No.A89) and Malha plot in the sublitharenite field wherethe samples of Abu Qada (S.No.A51&B106) and one sample of Raha (S.No.B96) and one sample of Matulla (S.No.B115) are in greywacke field.

The figure of log (SiO_2/Al_2O_3) versus log (Fe_2O_3/K_2O) according to Herron [10], (Figure 15) indicates that the samples of Raha & Abu Qada formations (S.No.B96&A51) plot in the shale field but the other sample of Abu Qada (S.No.B106) and Matulla (S.No.B115) plot in the Fe-shale field. On the other, the sample of the Matulla (S.No.A80) plot in the field of sublitharenite, while sample No.B110 plot in the Q-arenite field. The samples of sandstones of Matulla (S.No.A59, A66, A89) and Malha (S.No.B95) plot in the field of Fe-sand. The major element geochemistry of the studied clastic rocks can be shown by plotting Na_2O-CaO-K_2O ternary diagram according to Taylor & Mclennan [20], (Figure 16) for comparison. The figure shows that the studied Raha (S.No.A19) and Matulla (S.No.A66, A89& B110) sandstone samples show high concentration of K_2O relative to the average shale and upper continental crust and average sand while the Abu Qada (shale) and Malha (sandstone B95) and Raha shale (B96) have high concentration of K_2O relative to the average sand, upper continental crust and low concentration of CaO than upper continental and average sand. The Al_2O_3-(CaO+MgO)-SiO_2 ternary relationship (Figure 17) shows that Malha, Raha, Abu Qada and Matulla sandstone samples exhibit low SiO_2 content relative to average shale and upper continental crust.

The relationship between SiO_2 and K_2O/Na_2O (Figure 18) according to Roser and Korsch [18], indicates that the studied Matulla (sandstone and shale), Matulla (sandstone) plot in the passive continental margin field. On the other hand, Raha (sandstone and shale) plot in the ACM field while Abu Qada (S.No.B106) plot in ARC field.

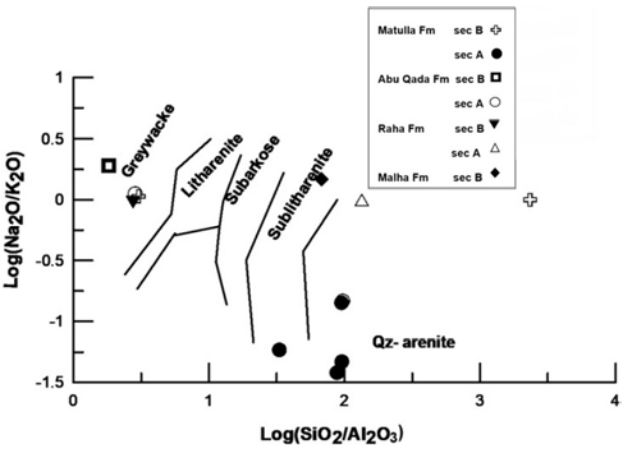

Figure 14. *Classification diagram of the studied clastic rocks (According to Pettijohn et al., [17].*

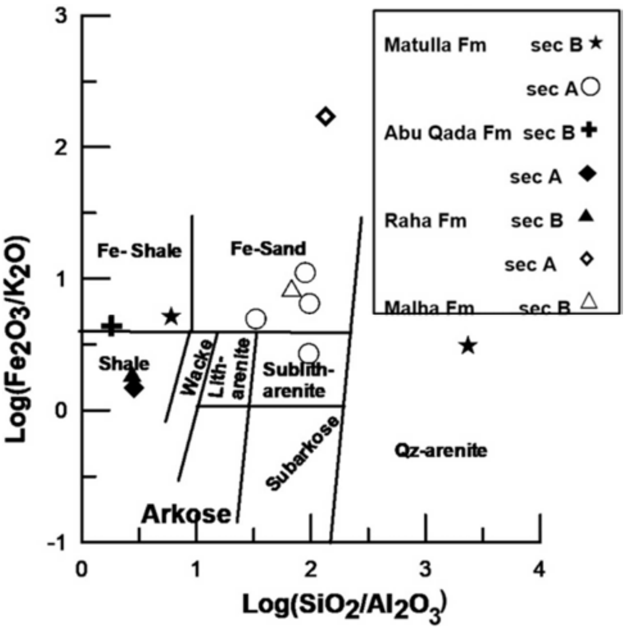

Figure 15. *Classification diagram of the studied clastic rocks (According to Heron, [10].*

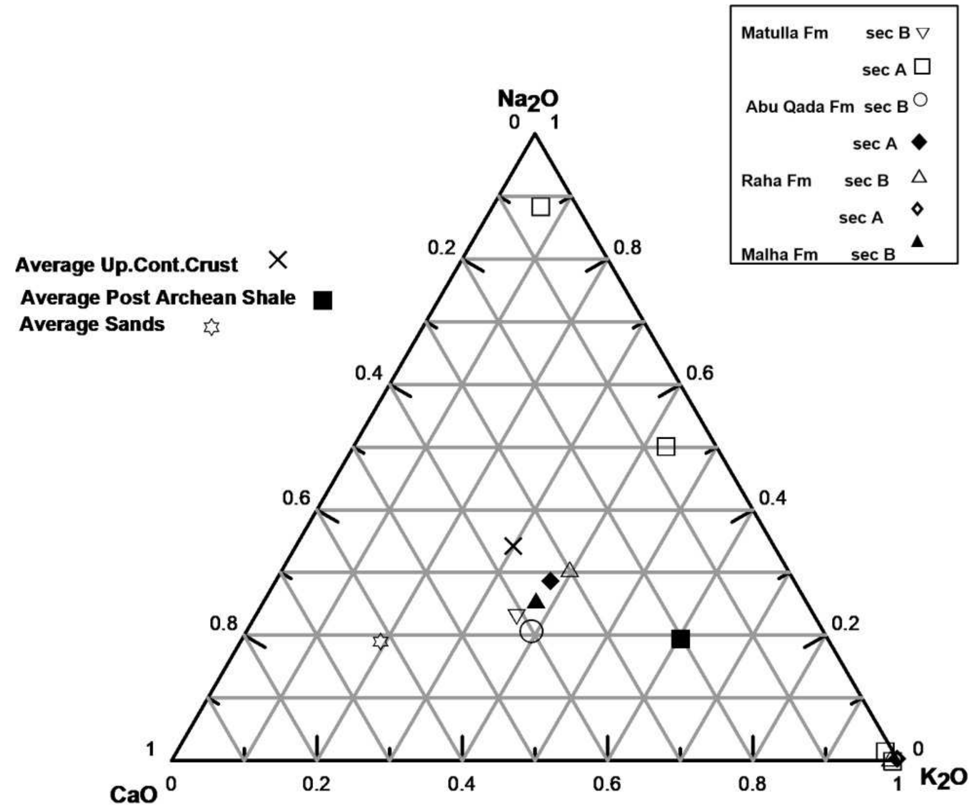

Figure 16. *Variation Na_2O, K_2O, CaO ternary diagram of the studied clastic samples Av. Up. Con. Crust, post Archean Shale, and Sands for comparison, According to Taylor and Mclennan, [20].*

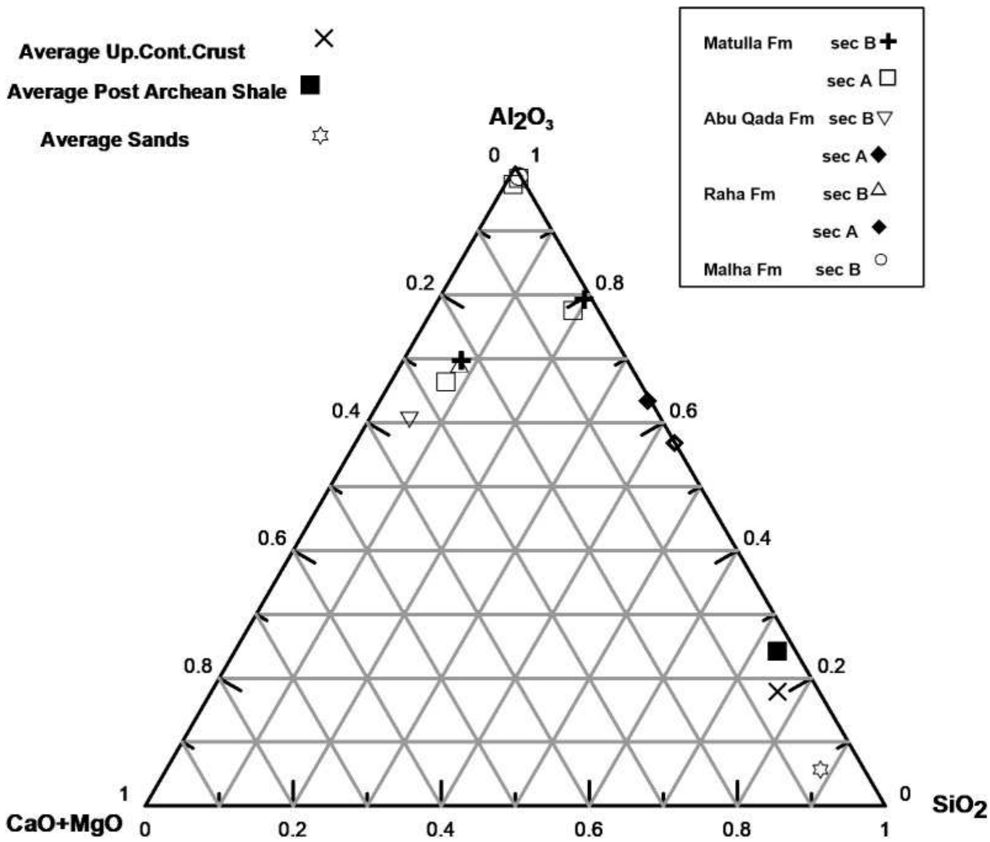

Figure 17. *Variation Al_2O_3, CaO+MgO, SiO_2 ternary diagram of the studied clastic samples Av. Up. Con. Crust, post Archean Shale, and Sands for comparison, According to Taylor and Mclennan, [20].*

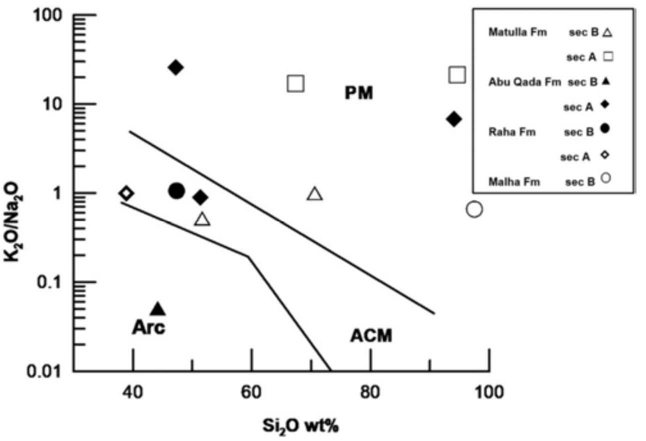

Figure 18. *Tectonic setting discrimination diagram of studied clastic rocks (According to Roser and Korsch, [18].*

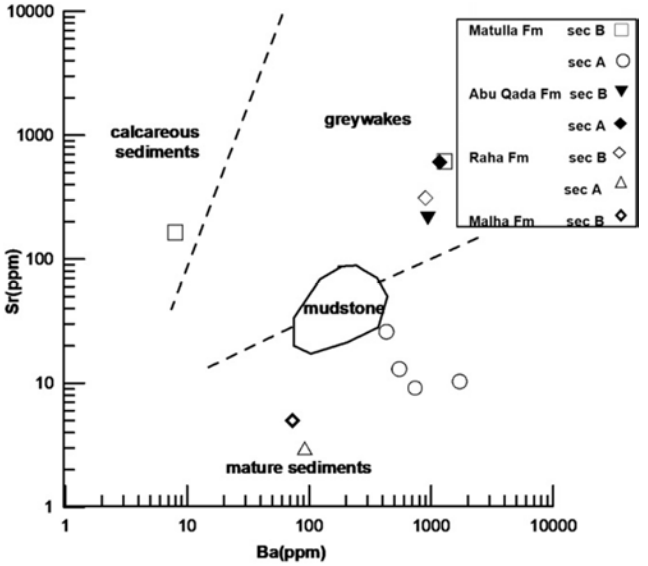

Figure 19. *Sr-Ba binary classification diagram of the studied clastic rocks (According to Floyed et al., [11].*

Trace elements: The relationship between Ba-Sr variation diagram (Figure 19) according to Floyed et al. [11], indicate that the samples of Abu Qada (shale), Matulla (clay) and Raha (shale) plotin the greywacke field while Malha, Raha, Matulla sandstone samples plot in the field of mature sediments except one sandstone of Matulla at calcareous sediments.

From the previous discussion, the following points are declared:

1. Samples from Raha, Abu Qada and Matulla are classified as greywacke (Ba-Sr diagram) and exhibit the characteristics of shale Pettijohn, [17] whereas the sample of Matulla is classified as calcareous sediments and exhibit the characteristics of Q-arenite Herron, [10].
2. Generally, the sandstone samples of the Malha, Raha and Matulla exhibit high SiO_2 and low Al_2O_3, Fe_2O_3, MgO, Na_2O and K_2O compared with the shale samples of Abu Qada, Raha and Matulla formations. Some sandstone samples of Raha (S.No.A19) and Matulla (S.No.A66, A89, B110) have high CaO compared with other samples.
3. The shale samples of Matulla exhibit Cu, V, Ba compared with Abu Qada and Raha shale probably due to the type of clay minerals in Matulla compared with clay minerals in Abu Qada and Raha shale.

4.2.3. Non-clastic (Carbonate) Rocks

The behavior and distribution of the major oxides are shown on figure 11.

The CaO contents show variation from ~54% in Abu Qada limestone (S.No.A48) to ~55% in Raha, Matulla and Sudr limestone (Figure 20). The dolomite limestone exhibits CaO content of ~48%in Abu Qada Formayion (section B) and ~36%-37% in Wata (section A) and Matulla Formation (section B). The previous CaO variation reflects the nature (type) of the studied limestones, i.e., either limestone in Abu Qada, Raha and Matulla in sections A&B and dolomitic limestone of Abu Qada, Wata and Matulla formations in sections (A&B).

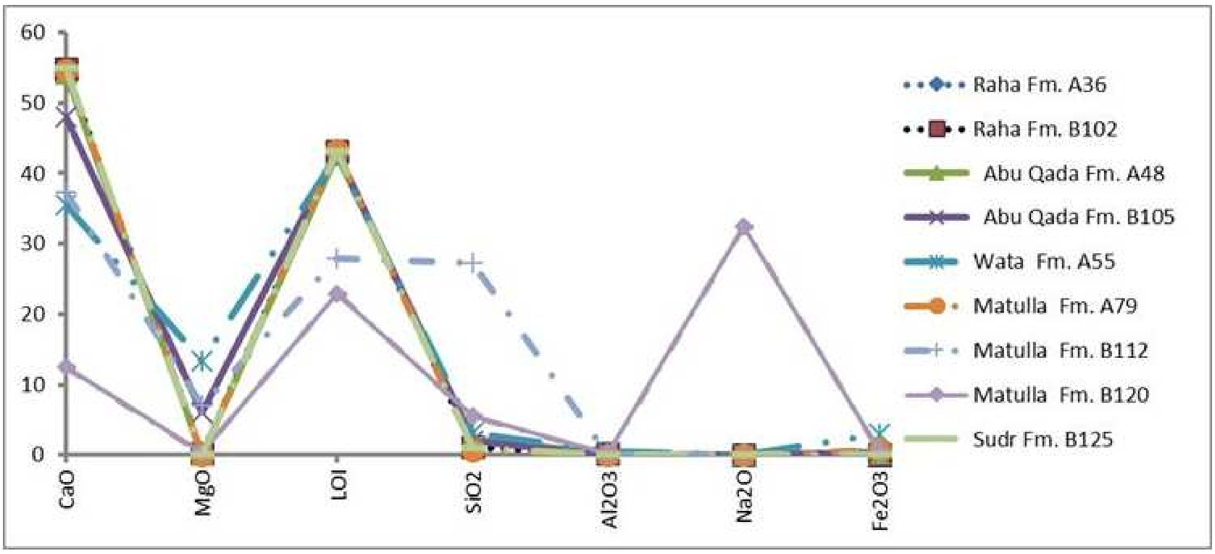

Figure 20. *Major oxide variation diagram of the studied non-clastic rocks, G. Qabaliat area.*

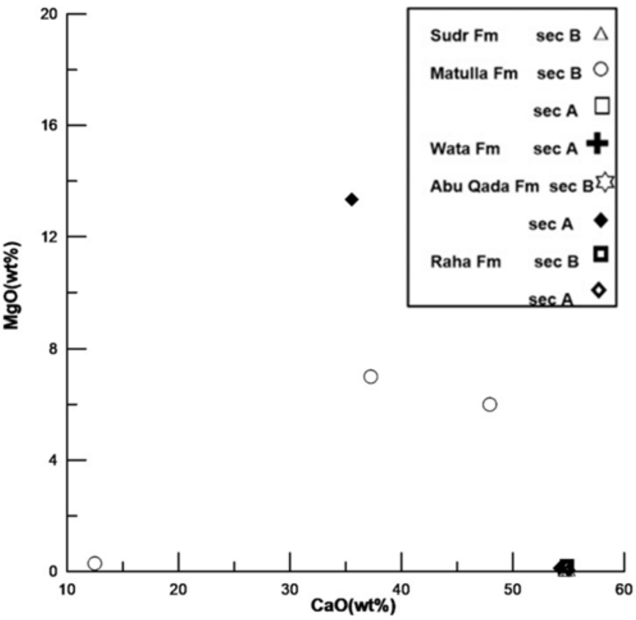

Figure 21. *MgO-CaO binary diagram of the studied non-clastic rocks.*

The MgO contents reflect a reverse order of CaO, i.e. decrease in Abu Qada limestone (S.No.A48) from 0.12% and 0.2%, 0.05% in Raha and Matulla limestone; dolomitic limestone from 6-13% and 7% of the Abu Qada, Wata, Matulla and Sudr formations. The increase and decrease behavior of CaO may indicate an oscillation of sea level either in Raha and Abu Qada or in Matulla formations.

The MgO versus CaO scatter diagram generally indicates that MgO increases on the expense of CaO (Figure 21) whichwas indicated previously from petrographic and XRD studies (presence of calcite and dolomite). Therefore, MgO content (dolomite) increases in the expense of CaO (calcite) may support the detected dolomitization phenomenon indicated from the microscopic study of the samples from sections (A&B).

The silica and alumina contents range in the limestone samples from ~1%-1.1%, ~0.1%-~0.2%, ~2%, 0.7-0.12% in Raha, Abu Qada and Matulla formations in the sections (A&B). The dolomitic limestone of the Abu Qada, Wata and Matulla formations have SiO_2 and Al_2O_3 contents ranging from 2%, 0.06%; ~3%, ~0.5% and ~27%, 0.11%, respectively in the two sections (A&B), Table 3, Figure 20.

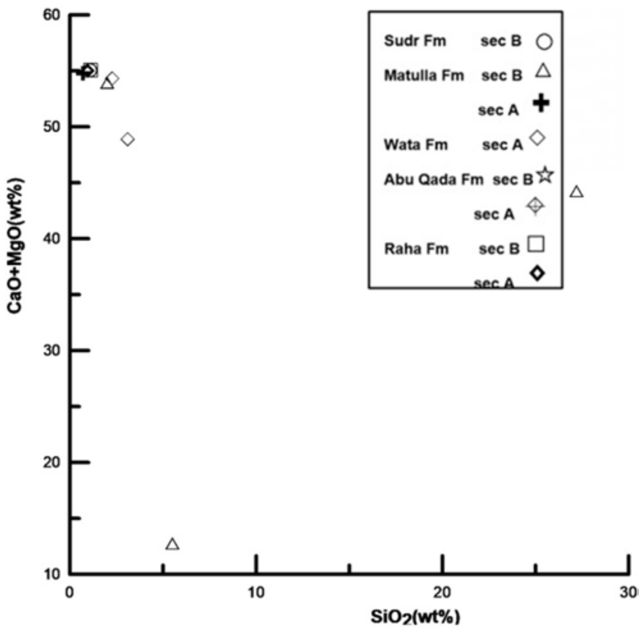

Figure 22. *SiO_2 versus (CaO+MgO) diagram of the studied non-clastic rocks.*

Table 3. *Major oxides (XRF%) and some ratios of some representative non-clastic samples, sections A&B, Gabal Qabaliat.*

Sp. No.	**Non-clastic rocks**								
	Raha Fm.		**Abu Qada Fm.**		**Wata Fm.**	**Matulla Fm.**			**Sudr Fm.**
Oxides%	**A36**	**B102**	**A48**	**B105**	**A55**	**A79**	**B112**	**B120**	**B125**
SiO_2	0.95	1.1	2.27	2	3.1	0.7	27.2	5.5	1.08
TiO_2	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.01
Al_2O_3	0.11	0.24	0.19	0.06	0.49	0.12	0.11	0.14	0.12
Fe_2O_{3t}	0.51	0.12	0.24	0.4	2.91	0.61	0.25	0.59	0.03
CaO	54.85	54.85	54.2	47.93	35.56	54.7	37.25	12.48	55
MgO	0.17	0.2	0.12	6	13.34	0.08	7	0.29	0.05
MnO	0.02	0.01	0.03	0.05	0.08	0.09	0.02	0.02	0.01
Na_2O	0.01	0.01	0.01	0.01	0.01	0.01	0.01	32.5	0.01
K_2O	0.01	0.01	0.02	0.01	0.13	0.01	0.01	0.01	0.01
P_2O_5	0.01	0.01	0.09	0.2	0.4	0.01	0.09	0.38	0.25
Cl^-	0.01	0.01	0.01	0.01	0.01	0.01	0.01	14.21	0.02
SO_3^-	0.01	0.01	0.01	0.01	1.2	0.01	0.01	10.33	0.01
LOI	43.1	43.1	42.62	43.1	42.48	43.3	27.9	22.96	43.22
Total	99.77	99.68	99.82	99.79	99.73	99.66	99.87	99.42	99.82
K_2O/Na_2O	1.000	1.000	2.000	1.000	13.000	1.000	1.000	0.000	1.000
SiO_2/Al_2O_3	8.64	4.58	11.95	33.33	6.33	5.83	247.27	39.29	9.00
log SiO_2/Al_2O_3	0.94	0.66	1.08	1.52	0.80	0.77	2.39	1.59	0.95
log Na_2O/K_2O	0.00	0.00	-0.30	0.00	-1.11	0.00	0.00	3.51	0.00
log Fe_2O_{3t}/K_2O	1.71	1.08	1.08	1.60	1.35	1.79	1.40	1.77	0.48
Fe_2O_{3t}+MgO	3.00	0.60	2.00	0.07	0.22	7.63	0.04	2.03	0.60

From the previous discussions and from Figure 20, a clear separation between the different varieties of the studied limestones was accomplished:

1. CaO define two groups, those of a high CaO (>~50%) and low MgO including Raha, Abu Qada, Matulla and Sudr limestone (sections A&B) and the other groups of CaO <~50% and high MgO including Abu Qada, Wata, and Matulla dolomitic limestone.
2. The dolomitic limestone of Abu Qada Formation (section A) has CaO content more than that of dolomitic limestone of Wata and Matulla formations (sections A&B).

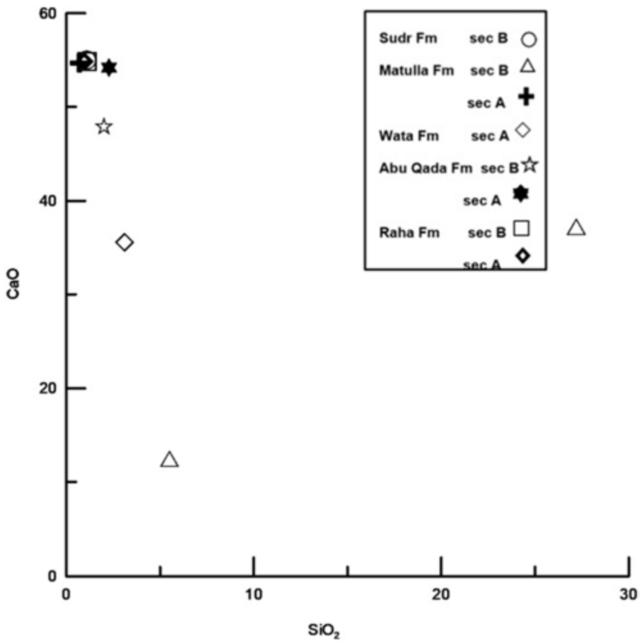

Figure 23. *SiO_2 versus CaO diagram of the studied non-clastic rocks.*

The SiO_2 content plot against CaO+MgO (Figure 22) exhibits a negative relationship. It is observed that the sample (S.No.B112) of the Matulla Formation in section (B) exhibits a high SiO_2 content, denoting the presence of Qz as geode. The SiO_2 content plot against CaO (Figure 23) exhibits a –ve relationship. SiO_2 define four groups, those of high SiO_2 ~27% represented in Matulls Formation by S.No.B112; SiO_2 ~3% represented by WataFormation (S.No.A55); SiO_2 from 1-2.2% as Abu Qada Formation (S.No.A48 &B105) than the other samples (SiO_2 <1% as in Raha, Matulla and Sudr formations). Also, Al_2O_3 content versus SiO_2 scatter diagram (Figure 24), shows a +ve relationship which mayindicate the presence of minor arigillaceous material in the studied rocks.

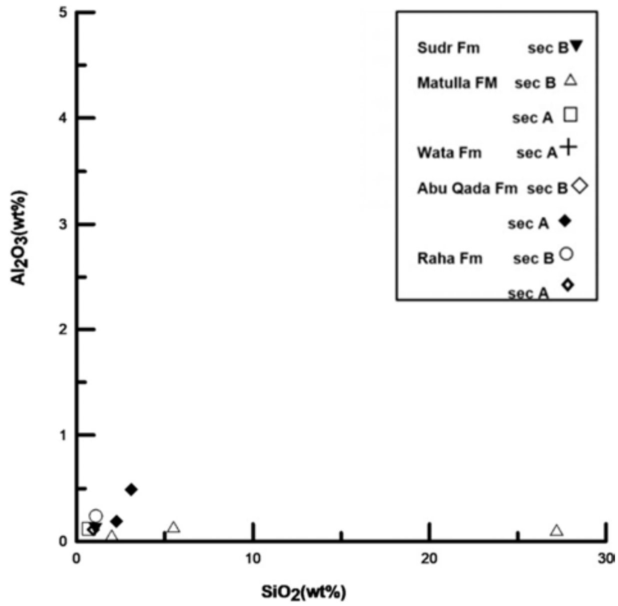

Figure 24. *SiO_2 versus Al_2O_3 diagram of the studied non-clastic rocks.*

Trace elements: the trace elements are determined in the analyzed samples representing limestones [Raha (S.No.A36 & B102); Abu Qada (S.No.A48); Matulla (S.No.A79) and Sudr (S.No.B125)] and dolomitic limestone [Abu Qada (S.No.B105); Wata (S.No.A55) and Matulla (S.No.B112)]. The behavior and distribution of trace elements (Table 4 and Figure 25) are outlined and discussed as follows:

The Ba and Sr contents of the studied limestones (Figure 25) reflect a separation between the different types, i.e. Ba content of more than 100 ppm define dolomitic limestone of the Wata Formation (S.No.A55) while Ba content <100 ppm defines the limestone and dolomitic limestone of Raha, Abu Qada, Matulla and Sudr formations.

Table 4. *Trace elements (ppm) of some representative non-clastic samples from section A& B, Gabal Qabaliat.*

Sp. No.	**Non-clastic rocks**								
	Raha fm		**Abu Qada fm**		**Wata fm**	**Matulla fm**			**Sudr fm**
Elements	**A36**	**B102**	**A48**	**B105**	**A55**	**A79**	**B112**	**B120**	**B125**
Cr	n.m	n.m	n.m	n.m	n.m	n.m	n.m	33	n.m
Ni	91	30	23	30	50	31	46	79	11
Cu	570	148	241	111	250	299	2409	566	86
Zn	531	124	160	96	342	308	1323	820	79
Zr	583	422	284	286	448	355	338	73	775
Rb	6	6	11	4	14	7	7	4	6
Y	8	5	4	4	9	5	4	29	9
Ba	40	30	41	47	102	59	49	88	39
Pb	20	4	3	5	11	7	33	43	4
Sr	209	152	111	90	132	128	115	4	289
Ga	2	2	u.d	u.d	3	u.d	3	31	u.d
V	17	9	11	21	36	13	17	4	26
Nb	8	5	5	3	6	5	4	12	10

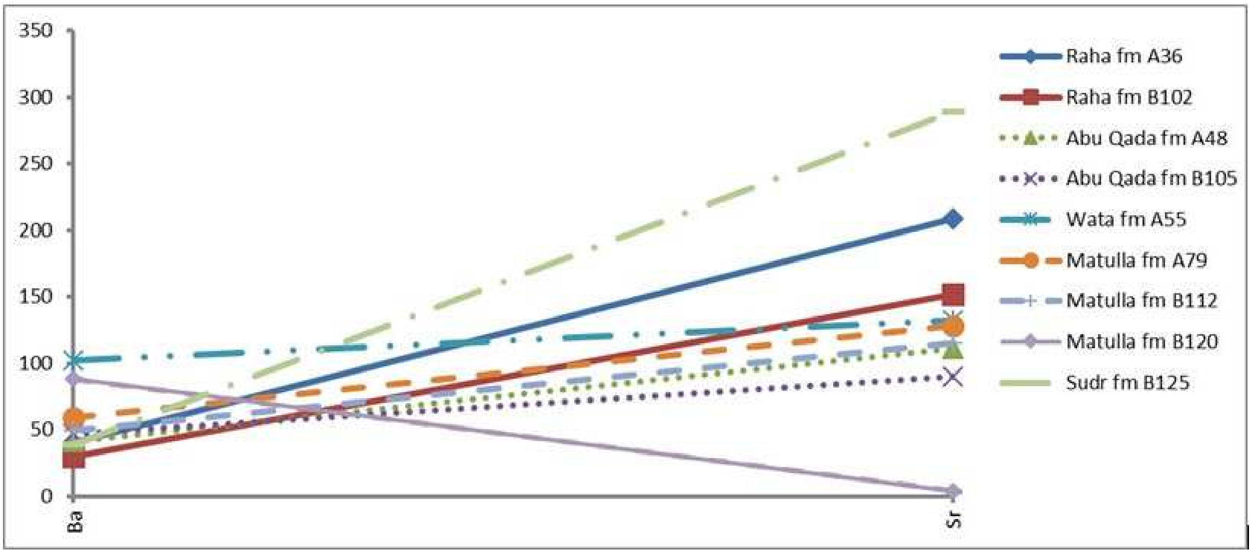

Figure 25. *Ba-Sr elements variation diagram of the studied non-clastic rocks, Gabal Qabaliat area.*

The same behavior is observed for Sr where >200 ppm define limestone of Raha and Sudr formations while Sr <200 ppm define the other types.

The removal of Ba in clays is caused by its greater ionic radius and lower ionic potential compared with Sr. Therefore, Ba is adsorbed in the hydrolyzates more strongly than Sr is, and the argillaceous sediments are the richest in Ba.

It is concluded from the previous discussions and diagrams that

1. Two groups were identified based on CaO and MgOcontents, the 1st group has >54% CaO and low MgO including Raha, Matulla and Sudr limestones while the other group including the more dolomitic facies of Abu Qada.
2. The dolomitic facies of the Abu Qada exhibit high CaO compared with the Wata and Matulla formations.
3. Four groups were identified based on $SiO_2$and CaO contents, the 1st group has <1% SiO_2 and >54% CaO including Sudr, Matulla and Raha limestones; the 2nd one has 1-2.2% SiO_2 and 47-54% CaO including Abu Qada samples; the 3rd one has ~3% SiO_2 and 35% CaO as in Wata dolomitic limestone and the 4th one has 27% SiO_2 and 37% CaO including dolomitic limestone of Matulla Formation.
4. Ba and Sr contents of limestone facies reflect a separation between the different types, where Ba contents of dolomitic facies are more tha their contents in limestone facies of Abu Qada, Wata and Matulla. The Sr contents have the opposite trend where Sr content of limestone are more than that of dolomitic facies (Raha and Matulla).

5. Conclusions

From the above discussion the studied Cretaceous rocks are distinguished into Malha, Raha, Abu Qada, Wata and Matulla formations.

The composite stratigraphic succession shows that the Malha Formation is composed mainly of argillaceous, ferruginous sandstone. The Raha Formation consists of shale, dolomitic limestone and limestone. The Abu Qada Formation consists of shale and sandstone with minor limestone, but the Wata Formation is composed of limestone with few shale beds. The Matulla Formation consisits of shale, sandstone and limestone, the Sudr Formation is composed mainly of chlak and chalky limestone.

Mineralogically, the X-ray diffraction analysis has been carried out to both bulk and clay samples. The data obtained of bulk samples for the Malha Formation are characterized by quratz, kaolinite, anhydrite, muscovite and calcite followed by dolomite. In the Raha Formation, it is characterized by the predominated either of calcite then quartz, kaolinite and gypsum or quartz, halite, hematite, muscovite, kaolinite and gypsum. In The Abu Qada Formation, it is characterized by quartz, halite, montmorillonite, kaolinite, muscovite and calcite or quartz, anhydrite, glauconite and hematite or quartz, halite, kaolinite, muscovite and montmorillonite. In the Wata Formation, the data reveal the presence of calcite, dolomite and quartz or calcite, quartz and hematite. In the Matulla Formation, it is characterized by calcite, dolomite, quartz, goethite, or calcite, quartz, halite, or calcite, dolomite, anhydrite, hematite, quartz, goethite or calcite, dolomite, quartz, apatite, hematite, goethite or calcite, dolomite, quartz goethite, hematite, muscovite, gypsum. In the Sudr Formation, the data reveal the presence of calcite only.

The X ray diffraction data obtained from clays are as follows: The Raha Formation is characterized by montmorillonite, saponite and kaolinite. The data from the Abu Qada Formation reveal the presence of kaolinite, saponite, montmorillonite or kaolinite, chlorite, saponite, illite and goethite or montmorillonite, saponite, chlorite = kaolinite, goethite. In the Matulla Formation the data reveal the presence of montmorillonite with minor illite or saponite, kaolinite or montmorillonite and saponite.

Geochemically, the studied clastic and non-clastic rocks reveal the following:

Clastic rocks: The studied sandstone samples have high SiO_2 and low Al_2O_3, Fe_2O_3, CaO, MgO, K_2O and LOI compared with the studied shale samples. Generally, the sandstone samples of the Malha, Raha and Matulla exhibit high SiO_2 and low Al_2O_3, Fe_2O_3, MgO and Na_2O and K_2O compared with the shale samples of Abu Qada, Raha and Matulla formations. Some sandstone samples of Raha and Matulla have high CaO compared with other samples. The studied Raha and Matulla sandstone samples exhibit high content of trace elements compared with the sandstones of Malha and Abu Qada formations probably due to the presence of minor iron, gypsum and halite in its lithic contents. The shale samples of Matulla exhibit Cu, V, Ba compared with Abu Qada and Raha shale probably due to the type of clay minerals in Matulla compared with clay minerals in Abu Qada and Raha shale. Samples from Raha, Abu Qada and Matulla are classified as greywacke (Ba-Sr diagram) and exhibit the characteristics of shale (Pettijohn diagram, 1972) whereas the sample of Matulla is classified as calcareous sediments and exhibit the characteristics of Qz-arenite (Herron, 1988). The studied Matulla shale sample (S.No.B115) exhibits high contents of Ni, Cu, Zn, V and Ba compared with Raha and Abu Qada shale samples (S.No.B96 andA51) probably related to the type of clay minerals in Matulla (chlorite) compared with montmorillonite mineral of Abu Qada shale. It is realized that the high Sr content at section (B, S.No.B115) 615 ppm of Matulla Formation and Raha Formation 312 ppm (S. no. B96) may be related to the calcareous nature of these samples. It is realized that the high Ba content of Matulla Formation (1289 ppm, S.No.B115) at section (B) and at section (A) the Ba content (1721 ppm, S.No.A51, Abu Qada Fm.) may be related to the presence of gypsum nodules.

Non-clastic rocks: The distribution diagrams clearly separate between the different varieties of the studied limestones. Those of high CaO and Low MgO. Two groups were identified based on CaO and MgO contents, the 1st group has >54% CaO and low MgO including Raha, Matulla and Sudr limestones while the other group including the more dolomitic facies of Abu Qada. The dolomitic facies of the Abu Qada exhibit high CaO compared with the Wata and Matulla formations. Four groups were identified based on SiO_2 and CaO contents, the 1st group has <1% SiO_2 and >54% CaO including Sudr, Matulla and Raha limestones; the 2nd one has 1-2.2% SiO_2 and 47-54% CaO including Abu Qada samples; the 3rd one has ~3% SiO_2 and 35% CaO as in Wata dolomitic limestone and the 4th one has 27% SiO_2 and 37% CaO including dolomitic limestone of Matulla Fm. Ba and Sr contents of limestone facies reflect a separation between the different types, where Ba contents of dolomitic facies are more than their contents in limestone of facies (Abu Qada, Wata and Matulla). The Sr contents have the opposite trend where Srcontent of limestone are more than that of dolomitic facies (Raha and Matulla).

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